TITLE: High Resolution X-Band SAR Constallation
for Risk Management

High Resolution X-Band SAR Constellation for Risk Management

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Summary:

This paper summarises the result of an ESA sponsored study on a Risk Management Earth Watch mission. The proposed system consists of a constellation of X-band SAR satellites so as to provide essential and complementary information with respect to other observing systems whether space or terrestrial. The mission requirements to meet both high spatial and temporal resolution, combined with fast data delivery led to two unique, alternative SAR-satellite designs which combine both the electronic and platform agilities.

1. Risk Management Mission

Risk management and monitoring constitutes one of the highest priority application fields of the European Remote Sensing Information Services (ERSIS [1]). It addresses specific aspects within various application areas such as resource monitoring (e.g. crops, forests, ship routing, geology, etc...) and assistance for the assessment of damage to environment, population and industries due to pollution and natural hazards (e.g. volcanic eruptions, earthquakes, hurricanes, floodings, etc...). The provision of information is required for assisting users throughout all three phases of risk management: namely the prevention, crisis and post-crisis phases.

Risk management and monitoring imposes most stringent observational requirements in terms of spatial resolution, temporal resolution and information delivery time. In particular, the high temporal resolution requirement inevitably leads to a satellite constellation including sensors in microwave spectral range in order to enable almost all-weather observations. A high-resolution SAR constellation therefore forms an essential component of such an observation system which shall also include sensors in optical spectral domain. The satellite-based system must be considered as providing complementary observations to those of terrestrial systems.

The potential users directly involved in the major disasters management are mainly public and governmental institutions, namely civil protections (national level), ministries (environment, defense, planning, fishery...), international and non-governmental organisations (UN, EU, Red Cross,...), scientific institutes, universities and specialised centres. There are also potential private users such as insurance, re-insurance companies, utility and transportation companies, industry and service companies in the area of geographical information and communications.

2. System Requirements

Table 1 summarises the most important system requirements. The centre-frequency has been selected so as to enable a maximum use of the allocated band for active sensing. A single polarisation has been specified as no specific requirement exists for dual-polarisation capability.

Most stringent requirements are placed on the revisit time, allowing quick responses of the system in emergency cases. An equally important requirement is the frequent delivery of INSAR products ($\leq 1 \sim 2$ days) for estimating e.g. ground movements or flooding extent in real-time.

The spotlight mode was not deemed necessary as 2m × 2m single-look resolution can be achieved in the strip-map mode. A noise equivalent σ^0 of $\leq$ -22 dB has been specified as a good mapping capability is required for large classes of surfaces. This value has been estimated from the published statistics of σ^0 over land [3]. A further effort is currently made by the Agency to analyse, to compile and to make available a statistical database of X-band σ^0 [4] for verifying the requirements.

The duty cycle/orbit/satellite will depend on the number of satellites in constellation: it can be as low as ≥ 5 min. for 6 satellites and increases to ≥ 10 min. for 3 satellites.

Frequency	9.65 GHz	
Polarisation	HH (or VV)	
Mean/max revisit	≤ 12/24 h	
INSAR mode	Repeat cycle ≤ 1 ~ 2 days	
Imaged swath width	Strip-map	ScanSAR
	≥ 20 km	≥ 140 km
Spatial resolution	Strip-map	ScanSAR
	≤ 2m × 2m (single-look)	≤ 25m × 25m (≥ 6 looks)
Noise equiv. σ^0	≤ -22 dB	
Total ambig. ratio	≥ 20 dB	
Duty cycle	≥ 5 ~ 10 min/orbit/satellite	
Satellite life	≥ 5 years	

Table 1: System requirements

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Further important requirements, which have been imposed on the system, are the cost efficiency and short time to mission implementation, implying a design with low technological risks and driven by cost.

3. Constellation Analysis

The revisit performance of the constellation is characterised by the mean and maximum revisit times which correspond respectively to the mean and maximum time intervals between two opportunities to image an arbitrary location on the Earth. They depend on the geographical location (latitude and longitude) and the selected orbit characteristics.

The requirement of global coverage imposes automatically polar orbits for the constellation. The remaining parameters are the number of satellites, whether sun-synchronous or not, the local nodal crossing time(s) if sun-synchronous, the mean altitude, whether the sensor shall view one side only or both sides of the satellite track, and finally the number of available incidence angles for any location. Sun-synchronous orbits with the 6PM/6AM Equator nodal crossing times have been preferred as they simplify the satellite power and thermal designs as well as they permit an identical design for all satellites, thus ensuring cost efficiency.

The most significant trade-off is between the number of satellites and the accessible swath-width for each satellite. The accessible swath width is necessarily limited through the requirements to meet the imaging performance (imaged swath width, spatial resolution, sensitivity and ambiguity ratio). A so-called Walker 6/1/0 constellation at 510 km offers an optimum solution with only one-sided viewing capability. It corresponds to a regular distribution of 6 satellites on a single orbital plane: each satellite has a 6-days repeat cycle with 91 orbits and the constellation has a one-day cycle with a circular permutation of the 6 satellites. This translates to a repeatable image acquisition geometry over any point on Earth every 24 hours by successive satellites, a particularly useful property for delivering INSAR products on daily basis. For global coverage, an accessible swath-width of 430 km is required, which is feasible from the 510 km orbit altitude. The resulting maximum revisit time is less than 15 hours for most of the latitude range and increases to 24 hours for polar regions.

A 430 km accessible swath width can be achieved by electronic beam-steering in the case of the active antenna based concept. A further extension of the swath is also possible by combining both the electronic and platform steerings in order to overcome the limitations of the active antenna such as grating lobes and gain losses for large steering angles. In this case, the incident angle range is expanded from 20°-53.7° to 10°-63° using roll-maneuvers of the platform, resulting in an accessible swath of 660 km. However, either the spatial resolution or the sensitivity (noise equivalent σ^0) would be degraded in those extended accessibility regions. Despite the degraded imaging performance, the introduction of those extensions would permit to reduce the mean revisit time by a significant amount (from 12h to 7.5h over the Equator).

Finally, a two-sided viewing capability can further improve the revisit characteristics of the constellation at the cost of a more complex satellite design (mainly the attitude and thermal controls). This is achieved by re-pointing the platform through the nadir direction around the roll-axis. Alternatively, the number of satellites in constellation can be reduced, but at the same time conserving the same revisit characteristics as in the case of one-sided viewing capability. Thus, the higher complexity of the individual satellites can be traded-off against their number in the constellation.

Table 2 summarises the result of revisit analysis for different cases of constellation. One can notice that a constellation of 4 satellites with two-sided view has almost the same performance as 6 satellites with one-sided view only. A reduction to 3 satellites would still provide an acceptable revisit performance, a case of interest during a progressive deployment of the constellation, or in case of failure of a satellite. Therefore, the two-sided viewing capability has been baselined.

Constellation	Mean revisit	Max. revisit
6 satellites with one-sided view	≤ 7.5 hours	≤ 15 hours for most latitudes
3 satellites with two-sided view	≤ 14 hours	≤ 22 hours for most latitudes
4 satellites with two-sided view	≤ 8 hours	≤ 14.5 hours for most latitudes
6 satellites with two-sided view	≤ 6 hours	≤ 14.5 hours for most latitudes

Table 2: Revisit characteristics of different constellation cases (all cases assuming 10°-63° access range)

4. SAR Satellite Designs

A number of instrument concepts have been considered during the study and traded-off each others. The baseline concept is based on a planar active antenna which offers the largest flexibility in terms of operational modes and compliance to all of the requirements.

A second best option has also been studied in details as a complementary study [5] as it offered a lower cost alternative with a slightly compromised performance. This alternative concept is based on an array-fed reflector antenna which is combined with platform agility (rapid re-pointing capability) in order to enable large accessibility. Both of those designs are described below.

4.1 Active antenna based design

The concept based on an active planar antenna consists of a 4m by 1.9m non-deployable array accommodated on a Skybridge type platform (see Fig. 1). The spacecraft is a so-called "longitudinal flyer" with its largest surface occupied by the planar array for generating a steerable, side-looking fanbeam. As no spotlight mode is required, the beam-steering is performed only in elevation.

A number of options exist for accommodating a solar array, the most attractive one being the configuration shown in Fig. 1. The array is attached along a rear-edge of the spacecraft parallel to the flight direction. The 4 panels of the array can be folded and stowed along a side-wall of the spacecraft for launch. No rotation of the solar array along the orbit is necessitated as the sun-aspect angle remains constant for the 6PM/6AM orbit. Such a configuration also minimises air-drag as well as mass-inertia around the roll-axis for enabling rapid roll-maneuvers.

Fig. 2 depicts the antenna design. It consists of 6x5 sub-panels, each one composed of 2 rows of 16 subarrays. The amplification is fully distributed among the 960 T/R modules (30x32). The proposed SSPA technology is ¼ μm PHEMT producing 7 W peak power with a duty cycle of 5 to 16.5 %. The subarrays are made of slotted aluminium waveguides which offer a low cost, but very low loss solution.

The instrument general block diagram is shown in Fig. 3.

The **processing unit** contains:

- a digital chirp generator followed by D/A converter and up-converter for achieving the required large bandwidth (≤220 MHz);
- a direct analogue quadrature demodulator followed by A/D converter and interpolator filter to reduce the sampling frequency.

The **RF unit** contains:

- an up-conversion chain to 9.65 GHz;
- a down-conversion chain to the baseband;
- Tx and Rx calibration circuits.

The **antenna subsystem** contains:

- an elevation power splitter followed by time-delay-lines for minimising signal dispersion while beam-scanning;
- 5 azimuth power splitters which feed the sub-panels;
- 30 sub-panels each of which contains a power booster, a sub-panel power splitter, 32 T/R modules and 32 subarrays;
- calibration power splitters.

Furthermore, the instrument contains a **radar control unit**, a **power unit** and a **500 Gbit solid state mass memory**.

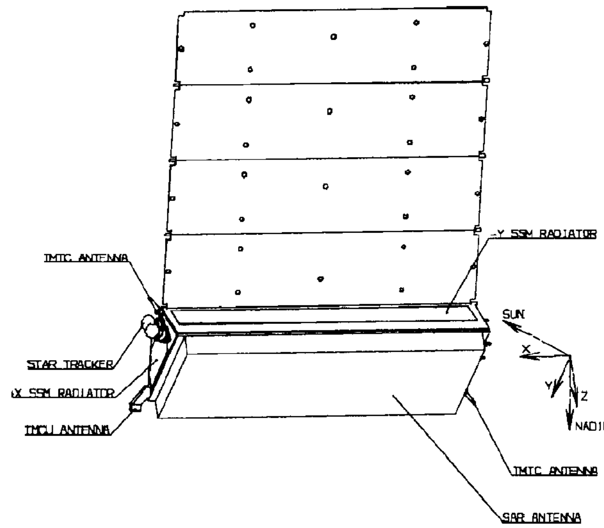


Fig. 1: SAR satellite configuration (active antenna based)

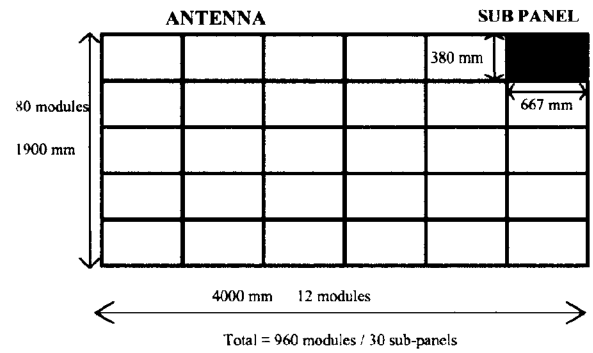


Fig. 2: Active antenna configuration

Two alternative architectures for the sub-panel design have been analysed. Those are:

1. A classical active antenna architecture where both the amplification and control (phase and amplitude) functions are imbedded within the T/R modules (see Fig. 4a).
2. An architecture borrowed from modern telecommunication satellite payloads where the control functions (phase and amplitude) are implemented within the sub-panel power splitter and the T/R modules are solely responsible for amplifications (see Fig. 4b).

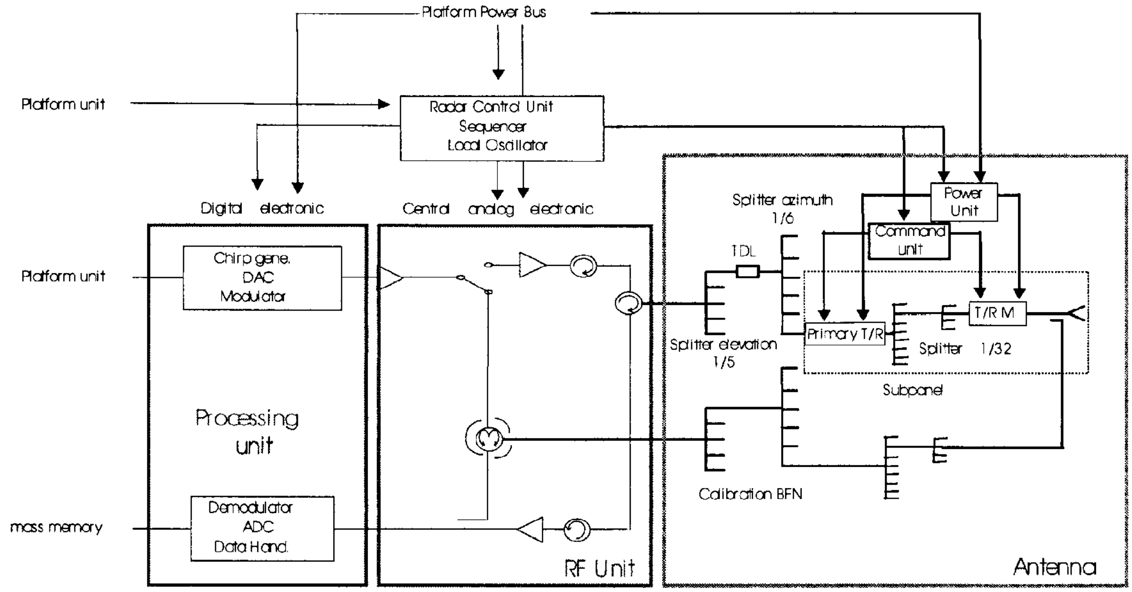
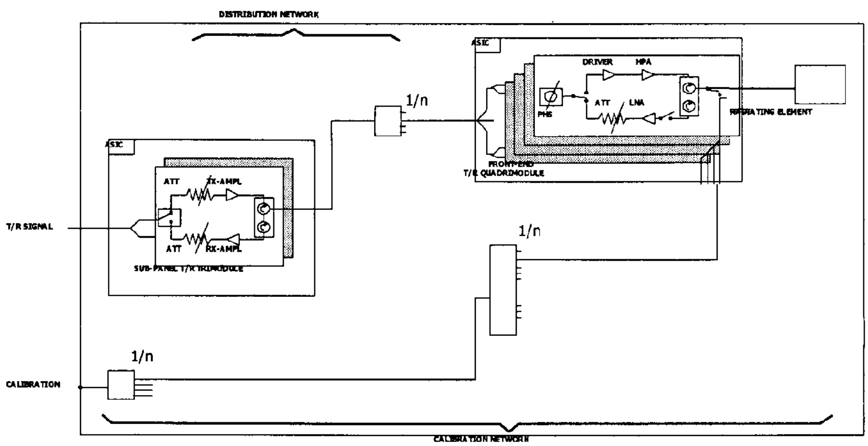
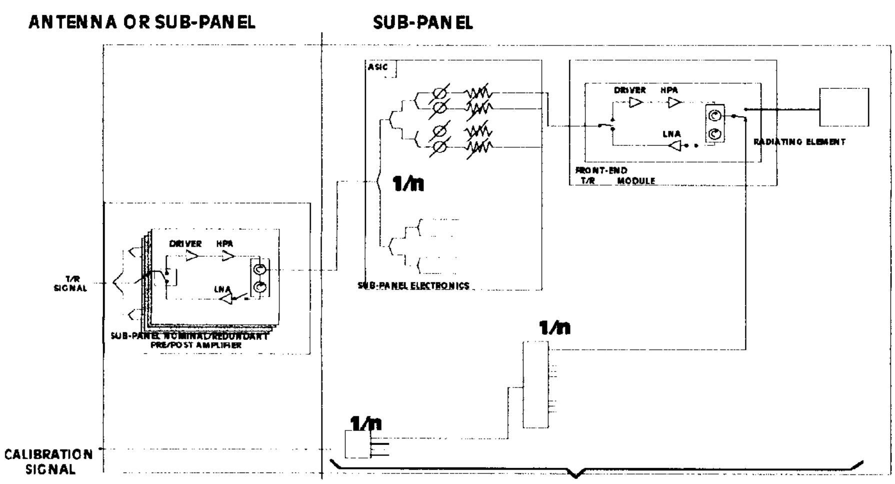


Fig. 3: SAR instrument general block diagram



a) Classical architecture with all functionalities implemented within the T/R modules



b) Alternative architecture where amplitude and phase control functions are moved from the T/R modules to the sub-panel power splitter

Fig. 4: Two alternative sub-panel architectures

The alternative architecture is particularly attractive for saving costs when the number of T/R modules is high as it minimises their complexity [6], which is the case for the considered SAR concept (960 T/R modules per satellite). By minimising the number of components which are required to be incorporated in the T/R module, their production costs can be reduced through:

- simpler design optimisation for serial production;
- shorter, thus faster assembly chain;
- shorter, thus faster verification and characterisation processes;
- higher yield, thus reduction of the overall number of T/R modules to be produced;
- simpler, thus faster identification of possible design flaws and simpler/faster design corrections.

From the instrument point of view, there are also significant advantages:

- reliability improvement of the T/R modules;
- reduction of the number of control cable connections to the individual T/R modules;
- phase and amplitude control circuits are placed in a better thermally controlled environment (away from the radiator surface and from the heat generated by the SSPAs.

The instrument parameters are summarised in Table 3. A maximum system bandwidth of 220 MHz is required for achieving a range resolution of 2 m at the lowest nominal incident angle of 20°. Below this limit, the range resolution will be degraded.

Orbit	510 km sun-synchronous 6PM/6AM Equator crossing
Accessible swath	20°-53.7° (electroninc steering) 10°-63° (platform steering) Two-sided viewing capability
Nominal Antenna pointing	33° from nadir (right-hand-side of satellite track)
Satellite roll angles	+17°/-10°/-53°/-66°/-83°
System bandwidth	≤ 220 MHz
PRF	≥ 4550 Hz
Operational duty cycle	≤ 5 min. per orbit over 3 consecutive orbits
Instrument mass	≅ 480 kg
Power consumption	≅ 4600 W DC in imaging mode
Solar array area	≤ 16 m^2
Data rate	≤ 800 Mbits/s after BAQ 8:4
Data storage	≤ 500 Gbits

Table 3: Summary of instrument parameters

The upper limit of the PRF depends on the ability of the synthesised beam to reject nadir returns. If the suppression of the nadir returns was possible for all beam positions, the PRF increase can be limited to 200 Hz. If they had to be avoided by choosing appropriate timings, the PRF can increase by more than 1500 Hz which could cause large increase in data rate. Hence, the former case has been assumed for the estimation of the data rate.

The operational duty cycle is limited mainly due to the high data rate of the SAR instrument. The indicated duty cycle has been derived by assuming one downlink possibility per orbit at 240 Mbits/s transmission rate.

The predicted sensitivity as a fuction of the incident angle (continuous line) is presented in Fig. 5 against a 95 % detection probability derived from the existing data [3] (= Specification Neσ^0). The sensitivity is excellent up to the incidence of 42°, but is somewhat marginal for the higher incidence range. Thus, the analysis has been repeated for a relaxed range resolution of 3 m (∝ 150 MHz system bandwidth). With the resulting improvement of 2 dB (broken line), the sensitivity becomes fully satisfactory.

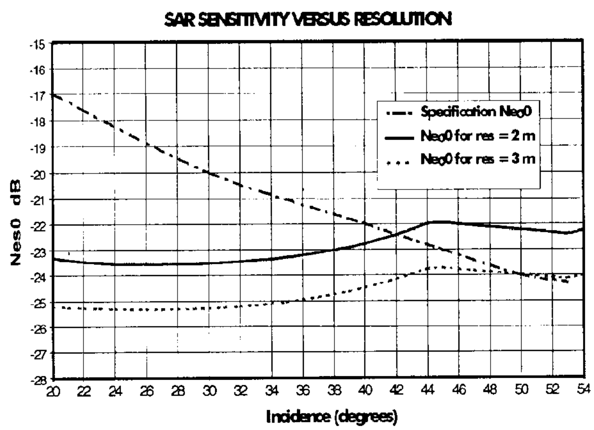


Fig. 5: Predicted noise equivalent σ^0 for 2 m and 3 m range resolutions

For a rapid deployment of the constellation, successive multiple launches are recommended for reducing the launch cost. The Skybridge launch approach can be adopted where the spacecrafts are attached to the launch keel dispenser through the –z spacecraft facing deck by means of interface fittings (see Fig. 6). Up to 4 spacecrafts can be launched in such a configuration. Fig. 6 shows an example of 3 spacecrafts stowed under the Soyouz/Fregate launch fairing.

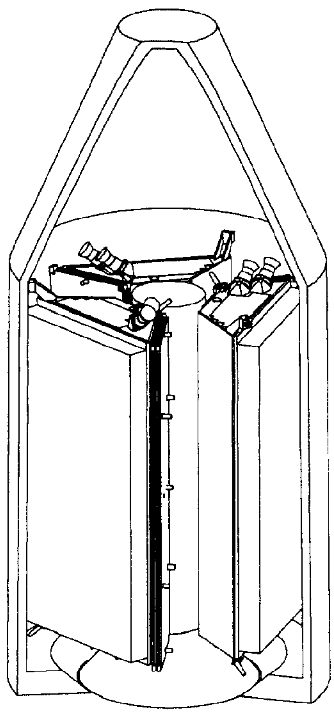


Fig. 6: Example of 3-spacecraft stowed configuration under Soyouz/Fregate launch fairing

4.2 Reflector antenna based design

The main motivation for studying a reflector antenna based alternative was its potential to achieve an acceptable performance at a significantly lower cost than the active antenna approach. The rational for such a cost reduction is based on:

- the potential to achieve an instrument at much lower mass than the active antenna one, which should enable the electronic agility of the active antenna to be replaced by the spacecraft agility;
- possible exploitations of synergy with modern telecommunication payloads technology, particularly in the area of light-weight, deployable, multiple-beam reflector antennas.

The large beam scanning range of the active antenna (+/- 15°) is difficult to achieve with a reflector unless it is oversized (e.g. 50 % increase in diameter). Consequently, the electronic scanning option has been discarded, which means that only the strip-map mode of the instrument is retained. This was felt to be acceptable as the constellation would still provide short revisit to progressively build up large area-coverages.

The selected solution consists of a 4 m diameter single offset reflector which is fed by a linear horn array (see Fig. 7). The degree of freedom offered by the array-feed enables synthesis of a beam with varying width which is optimised according to the viewing incident angle. Such an optimisation is mainly driven by the sensitivity (noise equivalent σ^0) and range ambiguity ratio requirements.

A preliminary system optimisation assuming an orbit altitude of 510 km led to the necessity to reduce the imaged swath width to 16 km for meeting the image quality requirements. A high peak power of 6 kW at a maximum of 16 % duty cycle is required from a cluster of TWTs. This reduction of swath width is due to the inability of the analysed reflector design to meet the tight beam-shape and gain requirements for achieving 20 km swath. This limitation arises because of:

1) the lower aperture efficiency of the reflector as compared to a planar antenna of the same size, as the aperture illumination is necessarily tapered in the former to avoid excessive spill-over losses. In order to achieve a comparable beam quality, the size of the reflector needs to be increased by approximately 20 %.
2) the lower number of degrees of freedom offered by the array-feed of e.g. 7 horns as compared to the 80 rows of the planar active array.

The preliminary analysis also identified a narrower incident angle range within which the image quality requirements could be met. A first estimate gave a compliant 20° - 50° range which corresponds to a 370 km accessible ground range. This would impact the number of satellites required in the constellation to meet the revisit requirements.

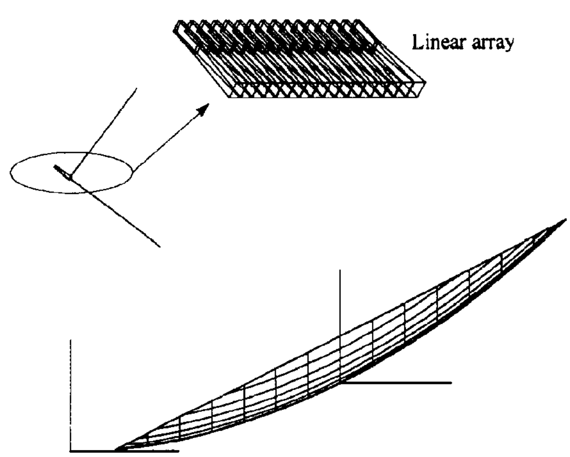


Fig. 7: Array-fed single offset reflector antenna configuration

A review of existing unfurlable reflectors has been carried out in order to find a solution for achieving a compact launch configuration for small satellites. The following 4 technology alternatives have been identified:

- Membrane-type reflector with flexible edges

- Thin stiffened reflector with foldable edges
- Wrap rib reflector
- Faggot or bundle using metallic unfurlable mesh

An analysis of platform accommodation showed that the faggot/bundle solution appears to be clearly the most convenient in terms of stowed dimension and ease of deployment. Two examples of accommodations using this solution are depicted respectively in Figs. 8 and 9 in deployed and stowed configurations. Fig. 8 shows a solution using a Skybridge type platform. In the stowed configuration, the faggot/bundle antenna has a form of a thin cylinder. Fig. 9 shows an accommodation on a Proteus type platform. Both of the configurations are so-called "transversal flyers".

The parameters of the reflector based SAR instrument have not yet been fully optimised at the time of writing, but they nevertheless are summarised in Table 4. Those values should be understood to be very preliminary and further optimisations will be carried out in the on-going study. In particular, the assumption on the orbit altitude is subject to review in an attempt to improve the overall performance. Estimation of the interface values such as mass and power will be consolidated after a more detailed design.

Orbit	510 km sun-synchronous 6PM/6AM Equator crossing
Accessible swath	20°-50° (platform steering) Two-sided viewing capability
Imaged swath width	≥ 16 km
System bandwidth	≤ 220 MHz
PRF	≥ 4500 Hz
Operational duty cycle	≤ 5 min. per orbit
Instrument mass	≅ 230 kg
Power consumption	≅ 3000 W DC in imaging mode
Solar array area	≤ 12 m^2

Table 4: Summary of instrument parameters (preliminary)

5. Conclusion

This paper presented two alternative SAR designs for a Risk Management Earth Watch mission. The active antenna based solution meets all the requirements, but is a complex instrument to build, test and operate. Some alternative active antenna architectures have been investigated for reducing technological risks.

The reflector antenna based solution appears to offer an attractive alternative for reducing the system costs but at a price of descoped capability. The feasibility of the concept is conditional upon the availability of unfurlable large (≅ 4 m) reflector technology. Such a technology is readily available in the US and in Japan. Further optimisations of the concept and assessment of technology are required before one could confirm the viability of this option.

Acknowledgement

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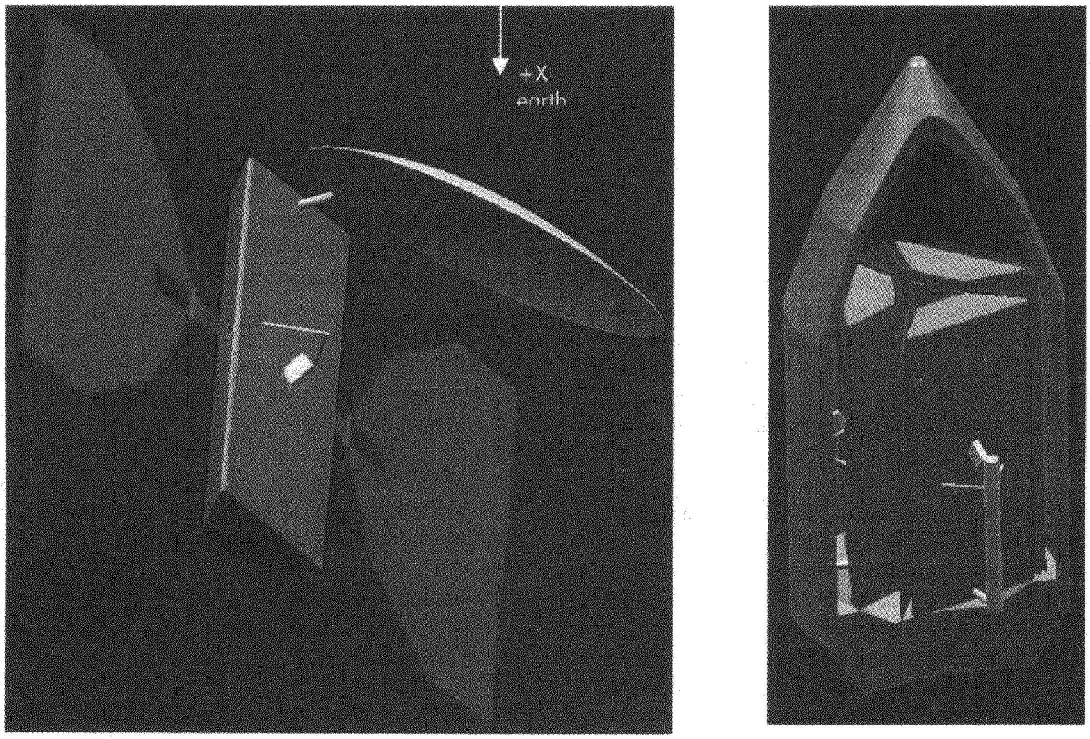

Fig. 8: Accommodation of faggot/bundle reflector antenna on a Skybridge type platform

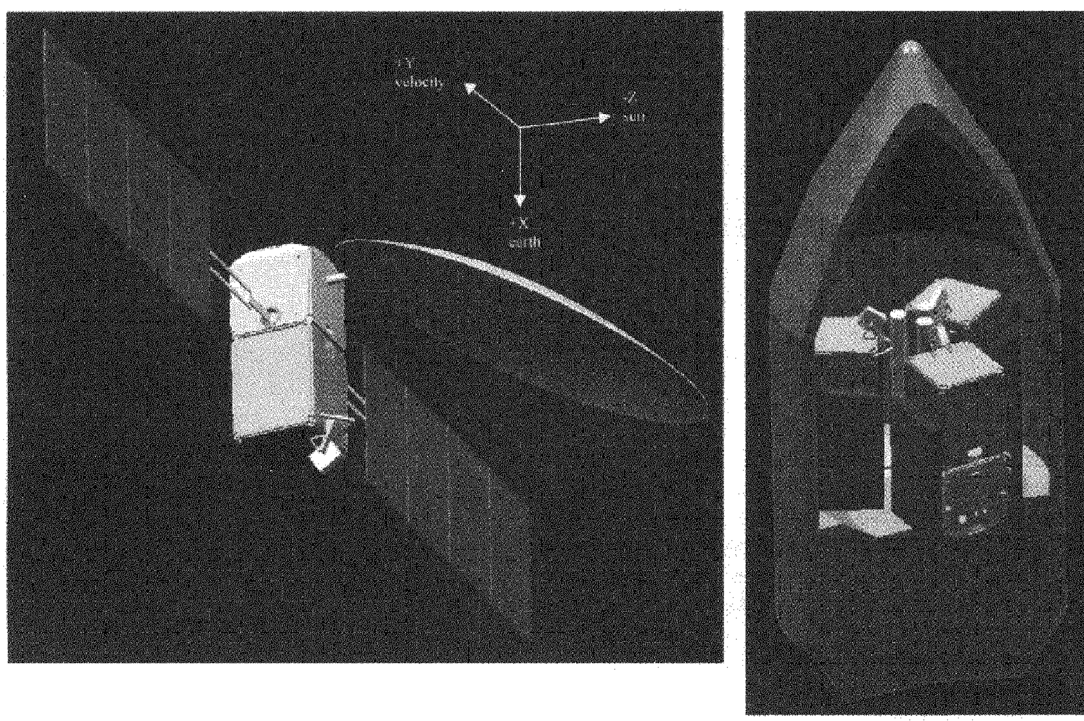

Fig. 9: Accommodation of faggot/bundle reflector antenna on a Proteus type platform